



Research papers

Hydromorphological processes of Dongting Lake in China between 1951 and 2014

Yawen Yu^{a,1}, Xuefei Mei^{a,1}, Zhijun Dai^{a,b,*}, Jinjuan Gao^a, Jingbao Li^c, Jie Wang^a, Yaying Lou^a^a State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China^b Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266061, China^c College of Resources and Environmental Sciences, Hunan Normal University, Changsha 410081, China

ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Marco Toffolon, Associate Editor

Keywords:

Hydromorphological processes
Water and sediment budgets
Anthropogenic activities
Dongting Lake
Changjiang (Yangtze) River

ABSTRACT

Under the impact of intensive anthropogenic activities and in the context of global climate change, the hydromorphological processes of most lakes around the world have changed dramatically. Here, based on hydrologic and topographic data, we analyzed secular variations in hydromorphological characteristics and their influencing factors at Dongting Lake, the second-largest freshwater lake in China. The entire time series (1951–2014) was divided into four subperiods based on the anthropogenic modifications of the Changjiang (Yangtze) River, including the construction of the Lower Jingjiang Cutoff Project and the operation of the Gezhou Dam (GD) and the Three Gorges Dam (TGD). The results indicated that there were obvious stepwise decreasing trends in the annual water discharge and suspended sediment discharge (SSD) from 1951 to 2014. Seasonal differences in water discharge and SSD over the recent 60 years exhibited a tendency of “less flooding during the flood season and more drying during the dry season”. Meanwhile, the deposition-erosion budget of Dongting Lake shifted from a deposition rate of 120×10^6 t/yr from 1951 to 2003 to an erosion rate of 2×10^6 t/yr with the serious degradation of the Ouchi and Xiangjiang deltas after 2003. The hydrological processes of Dongting Lake are dominated by different anthropogenic activities at different stages. The Jingjiang Cutoff Project is the main driver of the decreases in water discharge and SSD from 1967 to 1980. The operation of the GD along the Changjiang River and other reservoirs, as well as land-use changes in the Dongting Lake basin, should be responsible for the hydrological variations from 1981 to 2003. The high sediment retention rate, geometric adjustment of the channel, and flow regulation induced by the operation of the TGD are the main drivers for the hydromorphological variations in Dongting Lake in 2004–2014.

1. Introduction

There are 250 lakes with a surface area of more than 500 km² around the world, and they occupy only a tiny part of Earth's total land (Herdendorf, 1982; Lehner and Döll, 2004). Nonetheless, all of these lakes play an important role in maintaining regional and global ecosystem diversity, as well as providing basic survival conditions for humans, such as the water supply, economic resources, and even flood control (Kummu et al., 2011). However, most large lakes around the world are undergoing expansion or shrinking processes under the context of global climate change and anthropogenic activities. Examples include the majority of lakes in Tibet, Twelve Mile Lake in the USA, Lake Chad in Africa and Lake Urmia in Iran (Bianduo et al., 2009; Lemoalle et al., 2012; Jepsen et al., 2013; Alizadeh-Chooabari et al., 2016).

Dongting Lake, which is the second-largest freshwater lake in China with an area of 2623 km² and a volume of 16.7×10^9 m³, joins the middle Changjiang (Yangtze) River from the south. The lake directly gets 75% of its sediment and 34% of its water from the Changjiang River and is of vital significance for buffering flooding along the middle-lower Changjiang River (Nakayama and Watanabe, 2008; Wang et al., 2011). Located in a vast floodplain, Dongting Lake feeds a population of millions (Zhou, et al., 2016), and the hydromorphological processes of Dongting Lake therefore directly reflect the history of human anthropogenic activities.

Following the principle of “taking steel as the key link, taking grain as the key link”, over one-third of lakes in the Changjiang River basin were reclaimed to plow land accompanied by serious deforestation and soil erosion during the 1950s–1970s, and Dongting Lake is no exception, indicating that it has experienced dramatic deposition (Yin and Li,

* Corresponding author at: State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China.

E-mail address: zjdai@sklec.ecnu.edu.cn (Z. Dai).

¹ The first 2 authors contributed equally to this work.

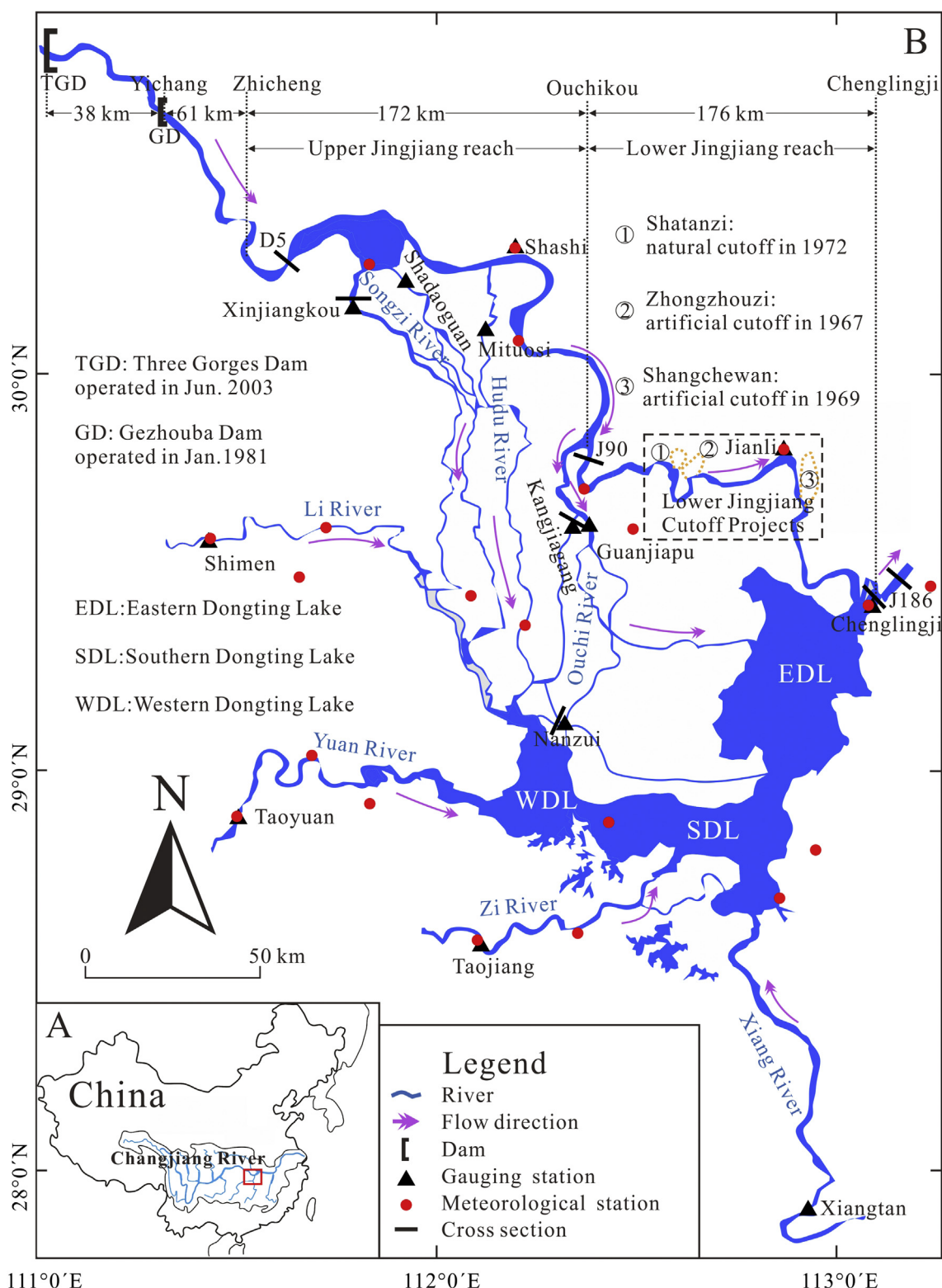


Fig. 1. (A) Location of the Dongting Lake basin in relation to the Changjiang (Yangtze) River; and (B) Dongting Lake basin and hydrologic/meteorological stations used in this study, with the black short line showing the position with available cross-section features.

2001; Xiang et al., 2003). Meanwhile, the Lower Jingjiang (Ouchikou-Chenglingji) Cutoff Project was implemented from 1967 to 1972 to improve the flood control capacity and navigation conditions of the Changjiang River. The shortened river length and decreasing sinuosity in the Jingjiang reach have altered the relationship between the Changjiang River and Dongting Lake (Yin et al., 2007).

Subsequently, a large number of dams were constructed in the Changjiang River basin and Dongting Lake system after the 1980s, including the most obvious examples of the Gezhou Dam (GD) and the Three Gorges Dam (TGD). The GD, which is located in Yichang (at the beginning of the middle Changjiang River), was operated in January 1981 with a storage capacity of $15.8 \times 10^8 \text{ m}^3$. Following the operation

of the GD, heavy siltation was detected in the region upstream of the dam site, while the riverbed below the dam experienced erosion (Chen et al., 2007). The heavy sediment trapping of the dam and further riverbed scouring after the implementation of the Lower Jingjiang Cutoff Project both decreased the sediment load from the Changjiang River to Dongting Lake (Yin et al., 2007).

Notwithstanding the significant decreases in inflow water and sediment following those previous anthropogenic modifications after the 1970s, Dongting Lake still maintained its deposition pattern (Yin et al., 2007). The history of deposition in Dongting Lake, however, was completely changed after the operation of the TGD. The TGD, which is currently the world's largest dam and is located along the upper reaches of the Changjiang River, has been in operation since 2003 and has had significant impacts on the hydrological regime in the middle and lower reaches (Dai and Liu, 2013; Mei et al., 2015, 2018; Li et al., 2016). With a large amount of sediment trapped in the reservoir, the SSD from the Changjiang River into the East China Sea has dropped from 423×10^6 t/yr to less than 135×10^6 t/yr, the downstream riverbed has transformed from experiencing seasonal erosion to year-round erosion, and the sediment carrying capacity below the dam has been greatly reduced (Dai et al., 2016; Lai et al., 2017). The alteration of river discharge and sediment transport in the Changjiang River resulted in the adjustment of Dongting Lake (Dai and Liu, 2013).

Therefore, there are increasing concerns regarding the impact of the TGD on the hydrological processes of Dongting Lake. Some research has indicated that the construction of the TGD was the dominant factor in the prolonged duration of low water levels and the declined inundation area of Dongting Lake (Lai et al., 2013; Yuan et al., 2015). Deng et al. (2012) showed that the replenishment ability of the Changjiang River in extreme drought years was higher than normal, despite decreasing flow and sediment diversion at the Three Inlets (i.e., the entrance of the Changjiang River). Meanwhile, recent studies have argued that Dongting Lake changed from exhibiting high siltation to erosion due to a TGD-induced decrease in the fluvial sediment supply (Yin et al., 2007; Zhu et al., 2014), which can significantly affect the lacustrine delta system. Xia et al. (2017) indicated that the channel variation in the Jingjiang reach of the Changjiang River tended to be influential in the discharge and flood-discharge capacity of the lake. Because they represent a complicated hydrographic net, when referring to hydromorphological alteration, the impacts of the main tributaries of the lake should not be neglected. Furthermore, the alteration of the hydrology and geomorphology of Dongting Lake are closely inter-connected. Therefore, it is essential to systematically understand the hydromorphological processes occurring under the influence of various potential factors, especially the impacts of the TGD. Such knowledge will be conducive to estimating the potential hydromorphological alteration of other large rivers of the world that are or will be affected by large dams. Here, the major purposes of this study are to (1) examine variations in the water and SSD of Dongting Lake from 1951 to 2014; (2) identify decadal morphodynamic changes in the lake; (3) and diagnose the possible driving factors of hydromorphological processes.

2. Material and methods

2.1. Study area

Dongting Lake ($28^{\circ}30'–30^{\circ}20'N$, $111^{\circ}40'–113^{\circ}10'E$), which is composed of three subbasins, namely, the Eastern, Western and Southern Dongting Lakes, is located at the confluence of the Changjiang, Yuan, Li, Zi and Xiang Rivers (Fig. 1). Thus, the lake responds to flood pulses of both the Changjiang and basin-wide tributary rivers. The Changjiang River annually supplies 89.5×10^9 m³ of water and 111.4×10^6 t of sediment to the Eastern Dongting Lake (EDL) and Western Dongting Lake (WDL) through the Three Inlets, namely, the Songzi River, Hudu River, and Ouchi River. The Southern Dongting Lake (SDL) and Western Dongting Lake (WDL) are fed by basin tributaries with an annual

average water discharge of 166.7×10^9 m³ and an annual average SSD of 26.3×10^6 t, including the Xiang River, Zi River, Yuan River and Li River, which are referred to as the Four Waters. Dongting Lake discharges water and sediment into the Changjiang River via Chenglingji, the only outlet from the lake to the river. The lake basin is affected by a subtropical monsoon, with precipitation concentrated from April–June (Wang et al., 2011). Seasonal rainfall leads to observable seasonal hydrological characteristics at Dongting Lake.

2.2. Data sources

The data included in this study comprises five groups. The first group includes mean daily water discharge and SSD data collected from 1951 to 2014 at the following eleven gauging stations: Xinjiangkou, Shadaoguan, Mituosi, Kangjiagang, Guanjiapu, Xiangtan, Taojiang, Taoyuan, Shimen, Chenglingji and Nanzui (available for 2007–2013) (Fig. 1). Water discharge was calculated as the product of measured flow velocity (measured by current meter) and the cross-section area. SSD was calculated as the product of water discharge and measured suspended sediment concentrations, which were measured at the surface, at depths of 0.2, 0.4, 0.6, and 0.8 m, and near the bottom (Dai et al., 2014). Both the runoff and suspended sediment measurements were collected from the Changjiang Water Resources Commission (CWRC) and were strictly examined following national standards. In addition, daily water discharge and water level data in the years of 2002 and 2014 at Shashi and Jianli in the middle Changjiang River were obtained from the CWRC.

The second group includes variations in deposition and erosion at Dongting Lake, which were calculated based on topographic maps from 1995, 2003, and 2011 at a scales of 1:10000 from the CWRC and Zhu et al. (2014). The topographic maps were first digitized using ArcGIS and then gridded into a resolution of 30×30 m using the Kriging method.

The third group includes the thalweg elevation (Oct. 2002 and Oct. 2013) data obtained along the Yichang-Chenglingji Reach and the cross-section morphology assessed at seven locations in the Changjiang River and Dongting Lake basin (Fig. 1). The river thalweg and cross-section surveys strictly followed national industry standards. Cross-section measurements were perpendicular to the mainstream direction. The section survey included land and underwater areas. The land measurement extended to 1 m above the highest historical flood level. For the underwater survey, the interval of measuring points was controlled within 5 m to ensure that feature points were included. The section survey was processed using an echo sounder and GPS-RTK. The thalweg elevation was obtained according to the distance between adjacent cross-sections and the maximum water depth point in the cross section. The CWRC organized the section survey and data compilation.

The fourth group includes yearly precipitation data obtained from 21 meteorological stations across the Dongting Lake basin from 1951 to 2014 (Fig. 1), which were collected from the China Meteorological Data Sharing Service System (available at <http://data.cma.cn/>).

The fifth group includes flow velocity data from 2007 to 2013 at the Chenglingji and Nanzui stations, which were measured by ADCP and obtained from the CWRC.

Before these data were published, they underwent a rigorous verification and uncertainty analysis. The specific data quality control method can be found in previous studies (Dai and Liu, 2013; Dai et al., 2014). Based on the collected data, monthly/yearly water discharge and SSD values, thalweg elevation differences, and seasonal SSD changes can be calculated. The deposition/erosion rates of Dongting Lake were computed from digital topographic maps of different years, while the down-cutting erosion rates of each cross-section were calculated based on the observed cross-profile differences during various years. The sum of water discharge through the Xinjiangkou, Shadaoguan, Mituosi, Kangjiagang, and Guanjiapu stations represented the contribution of the Three Inlets while the sum of water discharge

through the Xiangtan, Taojiang, Taoyuan, and Shimen stations represented the contribution of the Four Waters. The contributions of SSD from the Three Inlets and Four Waters were defined in the same manner. Then, the water/SSD that flowed into Dongting Lake was calculated as the total contribution of the Three Inlets and Four Waters, while the hydrological data at the Chenglingji station represented the outflow from the lake to the Changjiang River. Thereafter, the sediment budget of Dongting Lake was defined as the difference in the SSD between the inflow and outflow ($SSD_{Three\ Inlets} + SSD_{Four\ Waters} - SSD_{Chenglingji}$). In addition, the ratio of the water/sediment from the Three Inlets to the total input $\frac{SSD_{ThreeInlets}}{SSD_{ThreeInlets} + SSD_{FourWaters}} \times 100\%$ was defined as the water/sediment percentage of the Three Inlets. Similarly, the water/sediment percentage of the Four Waters was defined as $\frac{SSD_{FourWaters}}{SSD_{ThreeInlets} + SSD_{FourWaters}} \times 100\%$.

2.3. Data analysis

The Dongting Lake system has experienced the impacts of a series of hydraulic engineering projects, including the lower Jingjiang Cutoff Project, GD regulation and TGD regulation, from 1951 to 2014. To identify the influence of various anthropogenic activities on the hydromorphological processes of Dongting Lake, the entire time series (1951–2014) was divided into four subperiods based on the construction of the lower Jingjiang Cutoff Project from 1967 to 1972, the establishment of the GD in Jan. 1981 and the TGD in Jun. 2003, namely, the periods from 1951 to 1966, 1967 to 1980, 1981 to 2003, and 2004 to 2014.

Subsequently, two methods, including linear regression and the Mann-Kendall (MK) test were carried out to diagnose the temporal variation trends of water discharge and SSD (Mann, 1945; Kendall, 1970). Meanwhile, box plots were applied to detect the stepwise characteristics of water discharge and SSD over the subperiods (Tukey 1977; McGill et al., 1978), which involve the minimum, Q1 (the median of the lower half of the sample), Q2 (median), Q3 (the median of the upper half of the sample) and maximum values of the data series. To discern the seasonal fluctuations in water discharge and SSD during different periods, a series of parameters, including the coefficient of variation (C_v) and the water/SSD ratios of flood seasons (from May to October) to dry seasons (R_a), were applied in this study. Values of C_v were calculated using the Moment method (Greenwood et al., 1979). R_a was obtained directly from the monthly data. Normally, higher values of these parameters indicate obvious seasonal discrepancies.

3. Results

3.1. Variations in water and suspended sediment discharge

Both the total input and output of Dongting Lake in terms of its annual water discharge and SSD decreased significantly between 1951 and 2014 according to the results of the MK test (Fig. 2A and B). Meanwhile, distinct stepwise decreases were observed in the average annual input and output of water discharge and SSD over the four periods (Fig. 2A and B). Taking the average annual water discharge and SSD from 1951 to 1966 as reference levels, the average annual water discharge of the Three Inlets decreased by 38%, 54% and 67% from 1967 to 1980, 1981–2003, and 2004–2014, respectively. Meanwhile, the average annual SSD at the Three Inlets decreased by 41%, 60% and 96% over the latter three periods (Fig. 2C and D). Similar stepwise declining trends were observed in the SSD of the Four Waters after 1966, while its water discharge showed little change (Fig. 2C and D). For the total Inflow, Outflow, and Three Inlets, the statistical parameters of the maximum, Q3 and median values in the box-whisker plots showed obvious stepwise decreases during the four periods (Fig. 3). In general, the magnitude of the decrease in SSD was more remarkable than that in water discharge (Fig. 3). It must be emphasized that the

SSD output from the lake to the Changjiang River increased markedly after 2007 (Fig. 2B), which will be further discussed in the next section.

In addition, obvious seasonal fluctuations in water discharge and SSD were observed during the study period (Fig. 4). Over 60% of the annual water discharge was transported during the flood season at the Three Inlets, Four Waters and Chenglingji. For the contribution of sediment load during the flood season, the Three Inlets and Four Waters exhibited a high value of 80%. Over the past several decades, water discharge during flood seasons and dry seasons also presented distinct stepwise declines (Fig. 4A), and SSD showed an even more dramatic decrease than water discharge (Fig. 4B). At the Three Inlets, for example, water discharge during the flood seasons and dry seasons from 2004 to 2014 decreased by approximately 66% and 84%, respectively, compared to 1951–1966, while its SSD decreased by 95% and nearly 100%, respectively (Fig. 4B1). The declining R_a revealed a reduced distinction between flood seasons and dry seasons (Table 1). Thus, Dongting Lake seems to show a tendency towards “less flooding during the flood season and more drying during the dry season”.

3.2. Rating curves between water and suspended sediment discharge

The rating curves between monthly water discharge and SSD presented positive linear correlations at all sites (Fig. 5). However, the slopes of fitting curves decreased significantly during the given four stages. Notably, the most significant slope decrease was observed at the Three Inlets, decreasing from 1.85 in 1951–1966 to 0.29 in 2004–2014 (Fig. 5A1–A4), indicating that the descent rate of SSD was much greater than that of water discharge, especially from 2004 to 2014 (Fig. 3).

The patterns of the sediment rating curves of different sites also varied during different time stages (Fig. 5). During 1951–2003, the SSD at the Three Inlets was greater during the rising stage of the rating curve than that during the falling stage at the same flow conditions. The peak water discharge and sediment load values presumably occurred in July. However, the rating curve shifted counterclockwise from 2004 to 2014 (Fig. 5A5), with a smaller SSD during the rising stage for the same water discharge, when the maximum water discharge and SSD values appeared in July. Therefore, it could be speculated that the sediment sources changed under the impacts of climate change, human activities or both. The rating curve pattern of the Four Waters remained counterclockwise during the four stages with the sediment peak occurring during June, the rainy season when most storms occur (Fig. 5B5). The rating curve at Chenglingji showed a clockwise hysteresis loop over the past few decades, with the water discharge peak during either June or July, while the sediment peaked occurring during April or May (Fig. 5C5).

3.3. Sediment budget and sedimentary processes of Dongting Lake

The monthly sediment distribution at Dongting Lake showed that the sediment load was mainly transported during the flood season, when over 99%, 82% and 59% of the annual sediment transport occurred at the Three Inlets, Four Waters, and Chenglingji, respectively (Fig. 6A–C). Both the input and output SSD of Dongting Lake decreased sharply from 1951 to 2014, especially in flood seasons. Generally, the sediment budget of Dongting Lake decreased concurrently with that of the Three Inlets (Fig. 6D). Specifically, compared to 1951–1966, the average annual sediment budget at Dongting Lake subsequently decreased 35% from 1967 to 1980, by 34% from 1981 to 2003, and by 103% from 2004 to 2014 (Fig. 6D, Table 2). During the flood seasons and dry seasons, the sediment budget decreased by approximately 3%–57% and 48%–65%, respectively, compared to those of 1951–1966 (Table 2). Notably, the average annual sediment budget was negative from 2004 to 2014, indicating that Dongting Lake experienced erosion and provided sediment to the Changjiang River. It should be mentioned that the sediment budget of Dongting Lake could be overestimated due to a lack of data regarding sand mining, which requires further study.

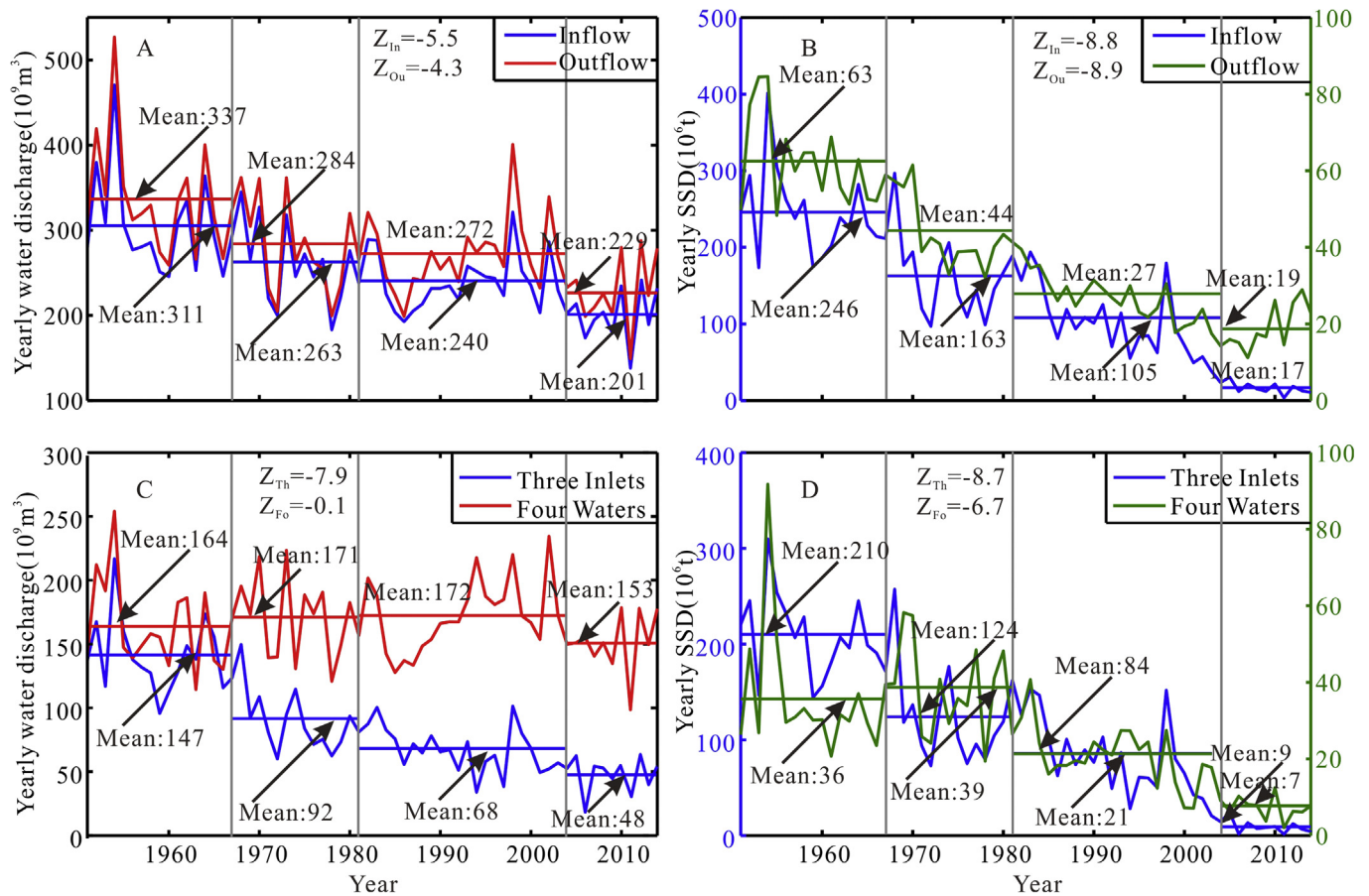


Fig. 2. Annual water discharge and suspended sediment discharge (SSD) series, with (A) Water inflow as the sum of Three Inlets and Four Waters and outflow at Chenglingji; (B) SSD inflow as the sum of Three Inlets and Four Waters and outflow at Chenglingji; (C) Water inflow at Three Inlets and Four Waters; and (D) SSD inflow at Three Inlets and Four Waters. The average values represent the annual mean in water discharge and SSD from 1951 to 1966, 1967 to 1980, 1981 to 2003, and 2004 to 2014, respectively. The values of Z indicate the Mann-Kendall trend test statistic at a 0.05 significance level.

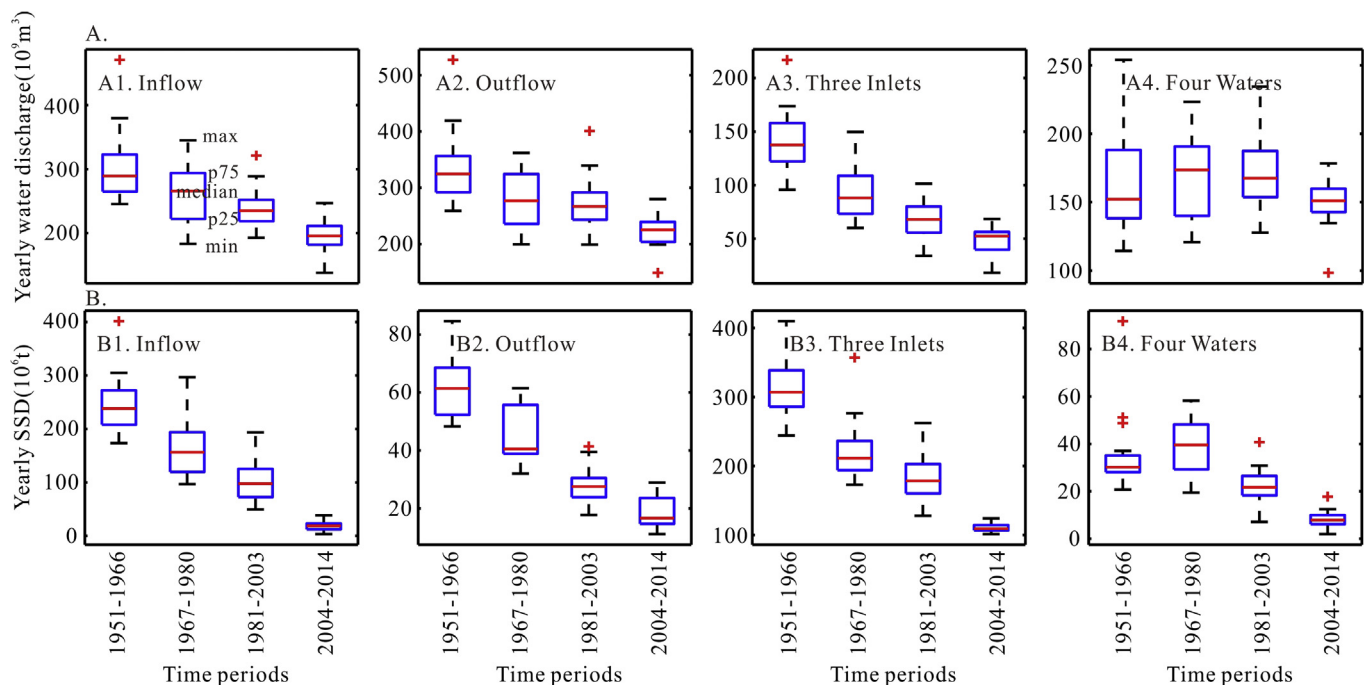


Fig. 3. Box-whisker plots of annual water discharge and SSD at Inflow, Outflow, Three Inlets and Four Waters from 1951 to 1966, 1967 to 1980, 1981 to 2003, and 2004 to 2014.

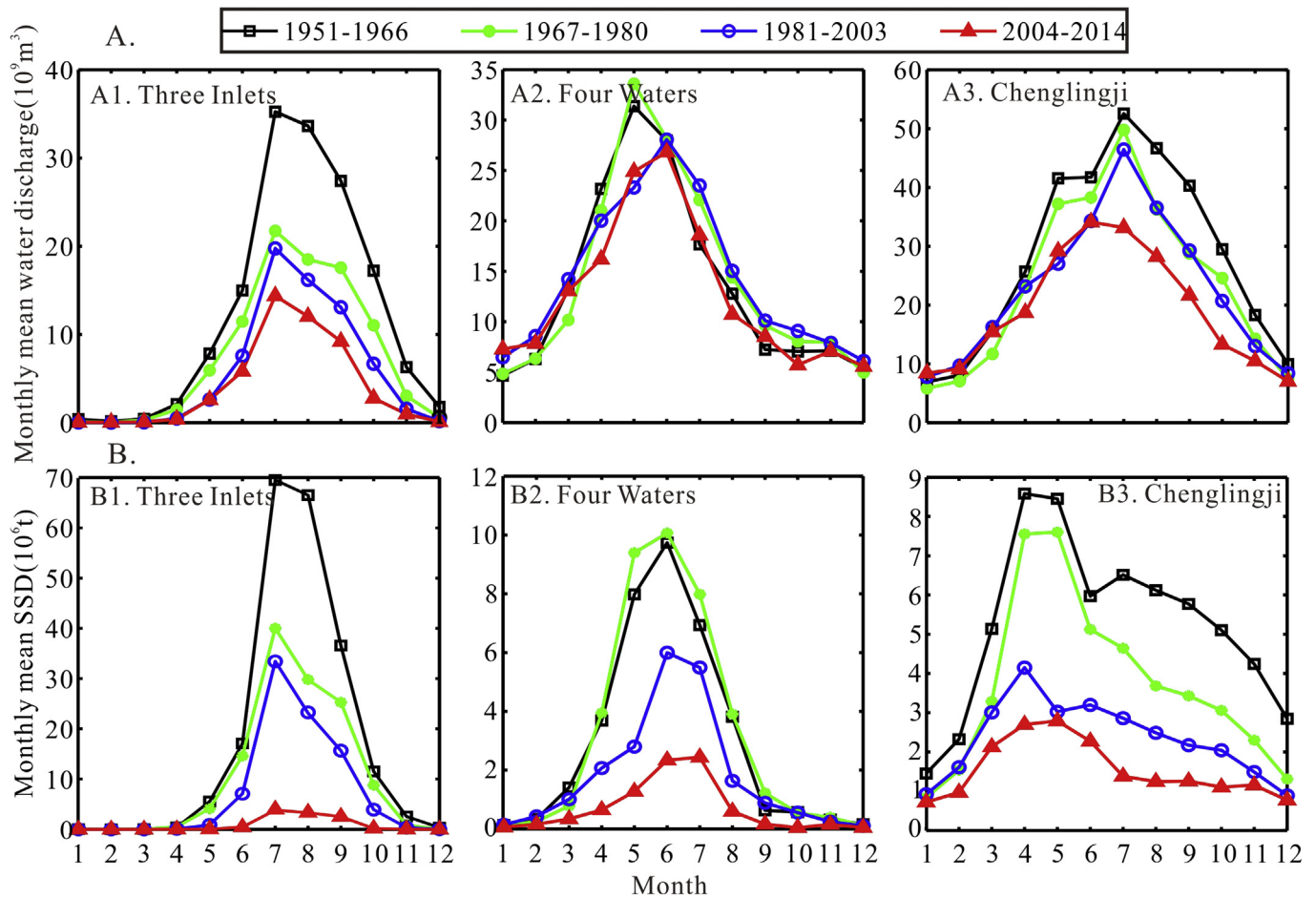


Fig. 4. Monthly mean (A) water discharge and (B) suspended sediment discharge (SSD) during four given periods at Three Inlets, Four Outlets, and Chenglingji.

Table 1

Summary of statistical parameters of monthly water discharge and suspended sediment discharge (SSD).

	Inflow (water discharge)		Chenglingji (water discharge)		Inflow (SSD)		Chenglingji (SSD)	
	C_v	R_a	C_v	R_a	C_v	R_a	C_v	R_a
1951–1966	0.6	3.4	0.6	3.0	1.3	25.1	0.4	1.5
1967–1980	0.6	3.3	0.6	3.0	1.1	22.2	0.6	1.6
1981–2003	0.6	2.7	0.5	2.5	1.4	23.8	0.4	1.3
2004–2014	0.6	2.5	0.5	2.4	1.2	11.5	0.5	1.2

Variations in the sediment budget can have a great impact on the sedimentation of Dongting Lake. The erosion-deposition pattern of Dongting Lake clearly changed from 1995 to 2011 (Fig. 7A1). Specifically, sediment in Dongting Lake was deposited continuously at a deposition rate of 0.41 cm/yr from 1995 to 2003, with the main deposition areas located in the northern part of the EDL, the eastern part of the SDL, and the western part of the WDL. However, sedimentation in Dongting Lake transformed from deposition to erosion between 2003 and 2011, with a mean erosion rate of 1.21 cm/yr (Fig. 7A2) (Zhu et al., 2014). Furthermore, the EDL exhibited the most significant change in the erosion-deposition pattern, followed by the SDL, while the WDL exhibited the most insignificant variation (Fig. 7A).

The morphological evolution of the delta within Dongting Lake was consistent with the sediment budget and erosion-deposition pattern variations of the lake. For instance, the Ouchi and Xiangjiang deltas, which are located at the EDL and SDL, respectively, received

replenishment from the Ouchi and Xiang Rivers and were both threatened by deltaic erosion due to insufficient sediment supply (Fig. 7B). The total area of the Ouchi delta declined significantly after 2003, with erosion mainly occurring in the middle zone, further fragmenting the delta at its tail part (Fig. 7B). Similarly, the total area of the Xiangjiang delta showed notable degradation after 2003, with the delta gradually breaking into multiple delta fragments (Fig. 7B).

4. Discussion

The long-term hydrological variations and morphological processes of the Dongting Lake basin and the Changjiang River are closely related to climate changes and anthropogenic activities (Dai et al., 2005; Yuan et al., 2015). Here, the possible impact factors on the hydro-morphological processes of Dongting Lake are discussed.

4.1. Precipitation in the Dongting Lake basin

Dongting Lake is located in the East Asia Summer Monsoon region. Water discharge over the lake basin is dominated by precipitation, which could be supported by the good correlation between basin precipitation and the water discharge of the Four Waters (Fig. 8A) (Zhang et al., 2007; Zhao et al., 2017). Because no significant trend was observed in basin precipitation from 1951 to 2014, the water discharge of the Dongting Lake basin (Four Waters) showed an insignificant trend during the same period (Fig. 2C, Fig. 3, and Fig. 8B). However, the SSD of Dongting Lake showed significant stepwise decreasing trends from 1951 to 2014 (Fig. 3). The different trends between basin precipitation and sediment load suggest that precipitation had little impact on the

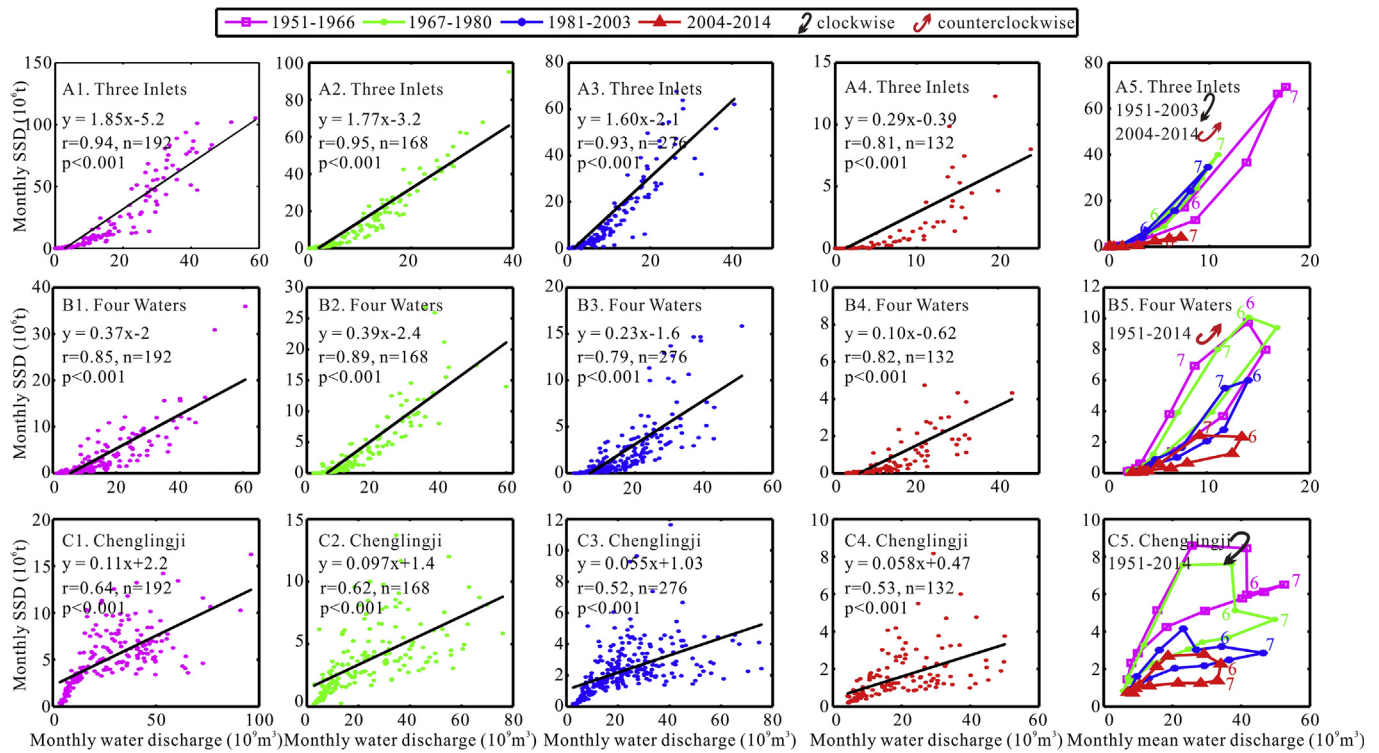


Fig. 5. Relationship between the monthly water discharge and suspended sediment discharge (SSD) at (A) Three Inlets; (B) Four Waters; and (C) Chenglingji, with A1, A2, A3, A4 showing the relationship between monthly water discharge and SSD during the four given periods; A5 describes the rating curve of monthly water discharge and SSD. The layouts of B and C row are similar to that of A row.

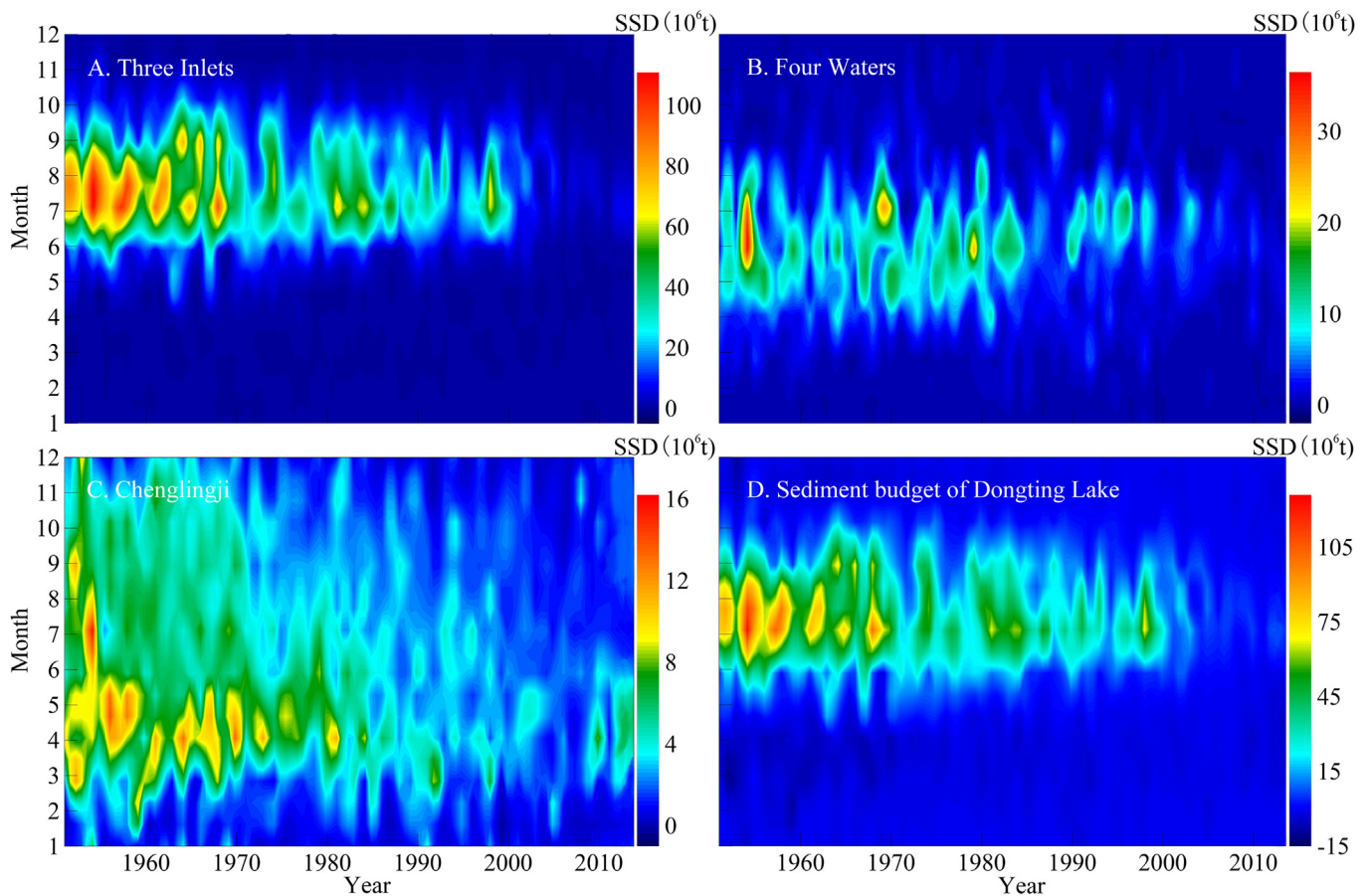


Fig. 6. Seasonal suspended sediment discharge (SSD) from 1951 to 2014 at (A) Three Inlets; (B) Four Waters; (C) Chenglingji; and (D) Seasonal sediment budget of Dongting Lake.

Table 2
Sediment budget of Dongting Lake during different time periods.

Period	Average sediment budget (10^6 t/yr)		
	Annually	Flood season	Dry season
1951–1966	183.32	198.47	–15.14
1967–1980	118.37	128.20	–9.83
1981–2003	77.61	85.20	–7.59
2004–2014	–2.33	4.99	–7.32

observed changes in sediment.

4.2. Anthropogenic activities in the Dongting Lake basin

Because it is obvious that the SSD variations in the Dongting Lake basin were not induced by precipitation, other potential factors likely caused the observed variations, such as human activities, including reservoir regulation and land-use changes (Du et al., 2011).

4.2.1. Reservoir construction in the Dongting Lake basin

According to previous studies, large amounts of sediment can be trapped in reservoirs without being diverted (Yang et al., 2007; Dai et al., 2014; Gao et al., 2015). In the Dongting Lake basin, 14,121 reservoirs have been constructed with a total storage capacity of 53×10^9 m³, including 47 large-scale reservoirs ($> 10^8$ m³) and 372 medium-scale reservoirs (10^7 – 10^8 m³) as of 2012 (China Census for Water in Hunan Province, 2013). The total capacity of large-scale reservoirs increased from 6×10^9 m³ in 1951–1966 to 9×10^9 m³, 28×10^9 m³ and 36×10^9 m³ in 1967–1980, 1981–2003 and 2004–2014, respectively (Fig. 9). Approximately 0.12% of this reservoir storage capacity was lost due to sediment deposition in the Dongting Lake basin (Sun and Fang, 2002). Given that the bulk density of sediment is 1.2 t/m³ (Dai and Liu, 2013), these reservoirs could have trapped 9×10^6 t/yr, 13×10^6 t/yr, 40×10^6 t/yr, and 52×10^6 t/yr of sediment during these four periods, respectively. The SSD at the Four

Waters increased slightly during the first two periods, then decreased significantly, especially during 1981–2003 and 2003–2013 (Fig. 2D). The drastic reduction in SSD from 1981 to 2014 was mainly caused by sediment retention in reservoirs, when the total reservoir storage capacity was 3–4 times larger than that from 1951 to 1980.

4.2.2. Land-use changes in the Dongting Lake basin

In addition, land-use changes in the Dongting Lake basin can also influence surface runoff, water yield and sediment discharge at the Four Waters (Sun et al., 2017). Due to a widely distributed granitic weathered zone, soil erosion is common in the Dongting Lake basin (Chen et al., 2004). From 1951 to the 1970s, serious deforestation and unreasonable land use resulted in severe soil erosion and caused 0.2 billion tons of soil loss in the lake basin (Zou, 1992). Therefore, the principle factor causing the increasing SSD from 1967 to 1980 was serious soil erosion in the Dongting Lake basin.

Following the severe and destructive flood of 1998, a program named “Return Land to Lake” was implemented, which controlled the loss of soil erosion to some extent, further decreasing the SSD over the period of 1981–2003 (Peng et al., 2005). After the construction of the TGD, along with prolonged droughts in Dongting Lake, some cultivated land and woodland were gradually developed (Jiang et al., 2016). Such variations may have changed the water infiltration and soil erosion within Dongting Lake, which could have indirectly affected the hydrological processes of the lake (Zhang et al., 2013; Deng et al., 2014).

Moreover, the SDL receives flow directly from the Four Waters; thus, changes in water discharge and SSD have observable effects on the morphological evolution of the SDL (Fig. 7). Under the impacts of precipitation, reservoir construction, and land-use changes, water discharge showed insignificant trends while SSD decreased significantly at the Four Waters during the different periods. It can be concluded that the fragmentation of the Xiangjiang delta can likely be attributed to the ‘hungry’ water produced by the non-synchronous changes between the water and the SSD.

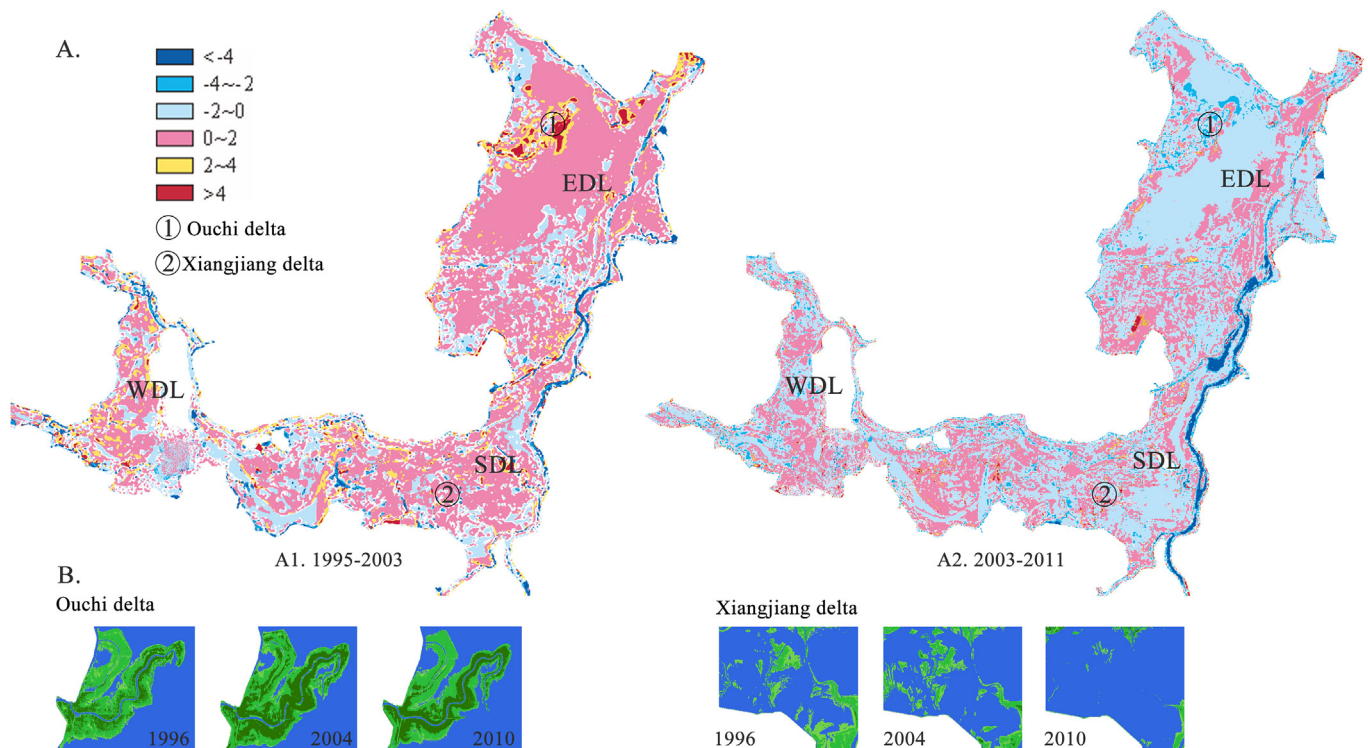


Fig. 7. (A) Deposition and erosion variation at Dongting Lake; and (B) Temporal variation of the Ouchi and Xiangjiang deltas at Dongting Lake.

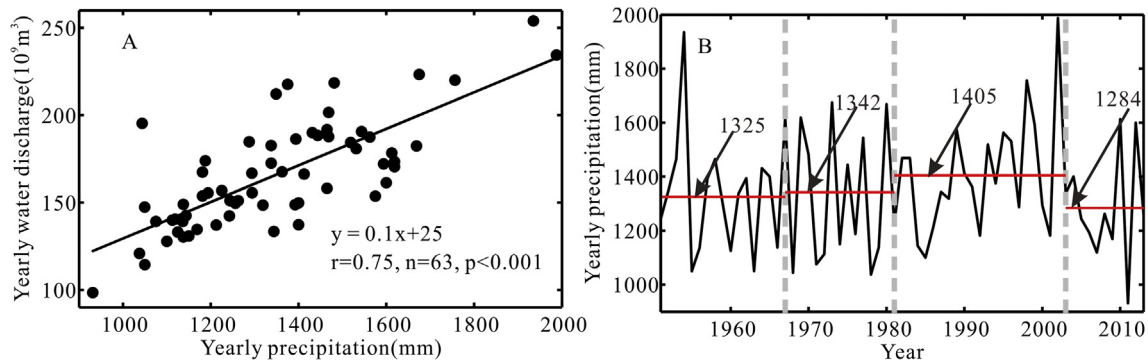


Fig. 8. (A) Relation between precipitation and water discharge at Four Waters; and (B) Annual precipitation of Dongting Lake from 1951 to 2014.

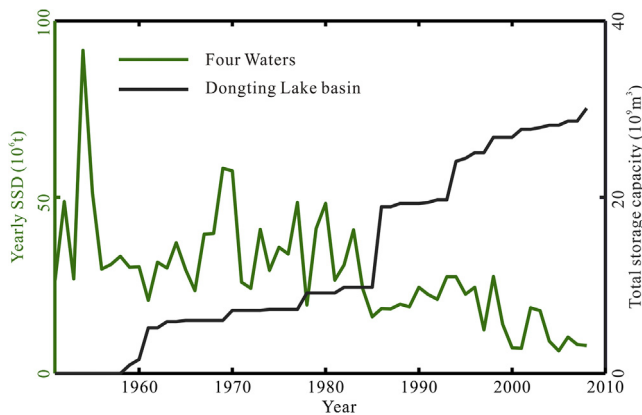


Fig. 9. Total storage capacity of reservoirs in the Dongting Lake basin and SSD of Four Waters.

4.3. Projects along the Changjiang River

Dongting Lake is directly connected to the Changjiang River by the Three Inlets (input of the lake) and Chenglingji (output of the lake), with more than 30% of the water and 70% of the sediment of Dongting Lake contributed by the Three Inlets (Fig. 10). Unlike the water discharge variations at the Four Waters, both water discharge and SSD

presented similar decreasing trends at the Three Inlets. Thus, the changes in water discharge and SSD at the Three Inlets were mainly controlled by intensive anthropogenic activities from the Changjiang River basin. Here, based on the hydraulic engineering construction projects implemented during different periods, we analyzed the impacts of the lower Jingjiang Cutoff Project and the GD and TGD impoundments on Dongting Lake.

4.3.1. The Cutoff Project in the lower Jingjiang reach

A series of changes occurred in the lower Jingjiang reach after the cutoff project, including a river length shortening of 80.6 km, a decrease in sinuosity from 2.83 to 1.93, and a hydraulic gradient increase (Fig. 1) (Yin et al., 2007). The evolution of the lower Jingjiang reach slowed until the channel in the reach achieved a new balance in 1980 (Tang, 1999). Thus, the effects of the Jingjiang reach Cutoff Project were concentrated from 1967 to 1980.

The ratio of the water/sediment diversion at the Three Inlets apparently decreased from 1967 to 1980, suggesting that much less water and sediment could enter Dongting Lake through the Three Inlets (Fan et al., 2008; Hu et al., 2015). Meanwhile, dry days at the Three Inlets increased considerably, such as at Guanjiapu along the Ouchi River where they increased from 17 days/yr from 1951 to 1966 to 117 days/yr (Deng et al., 2012). Consequently, water discharge at Three Inlets decreased much more remarkably than it did during the other periods due to the Jingjiang Cutoff Project (Figs. 3 and 10).

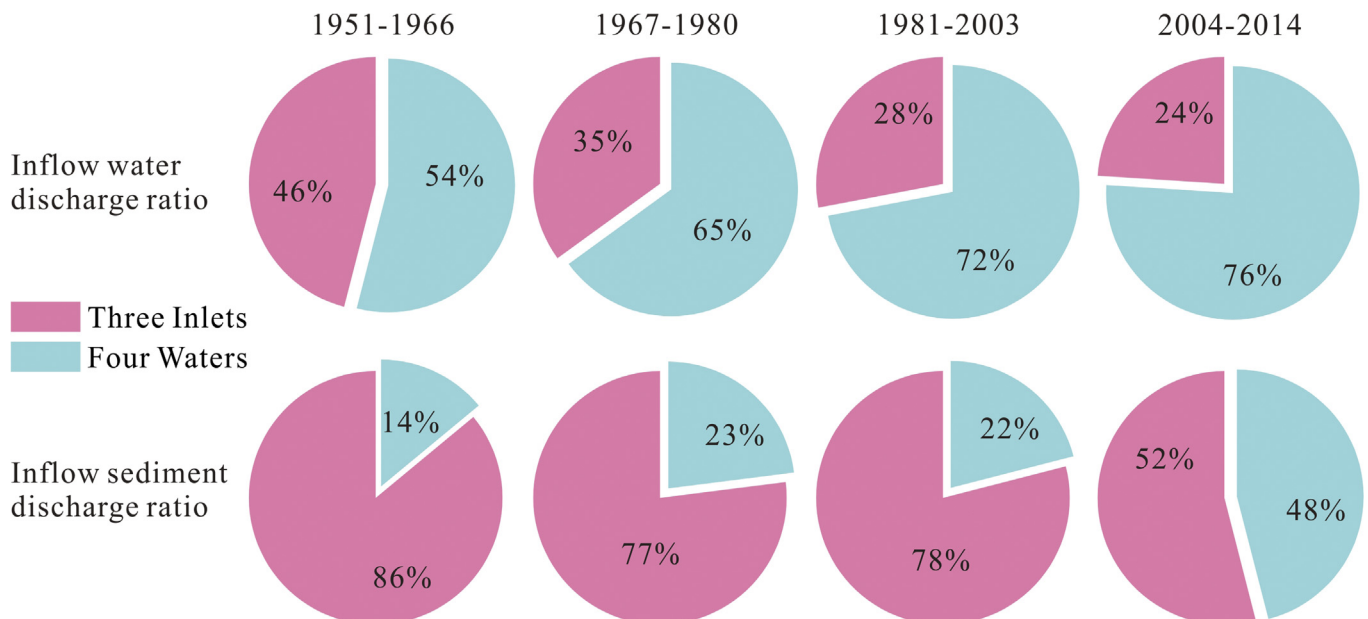


Fig. 10. Ratios of water discharge and SSD inflow at Three Inlets and Four Waters.

Water discharge at the Three Inlets decreased remarkably due to the impact of the Jingjiang Cutoff Project, thereby affecting the sediment transport. The SSD of the Three Inlets dropped by 41%, from 210×10^6 t in 1951–1966 to 124×10^6 t in 1967–1980, with the SSD during the flood season reduced by nearly 50% (Fig. 4B and Fig. 6A). As the most important source of sediment for Dongting Lake, the percentage of SSD from the Three Inlets was 86% from 1951 to 1966, but it declined remarkably to 77% from 1967 to 1980 after the construction of the Cutoff Project in the lower Jingjiang reach (Fig. 10). The decrease in SSD and SSD percentage at the Three Inlets indicated that the Cutoff Project played an important role in the sediment changes at Dongting Lake.

4.3.2. The regulation of the GD and TGD

By 2013, more than 50,000 dams had been constructed along the Changjiang River, which caused a dramatic decrease in fluvial sediment and led to substantial geomorphologic changes (Yang et al., 2005; Dai and Liu, 2013). Both water and SSD at the Three Inlets have presented declining trends since the impoundment of the GD in Jan. 1981. In addition, the decrease in water percentage at the Three Inlets suggested that the GD had more of an influence on water discharge than it did on SSD (Fig. 2D and Fig. 10).

The TGD, the largest dam in the world, has a storage capacity of 39.3×10^9 m³, which is nearly 25 times that of the GD. Notably, the SSD and SSD percentage of the Three Inlets decreased most significantly during the period of 2004–2014 (Figs. 2 and 10). The SSD dropped from 87×10^6 t/yr from 1981 to 2003 to 9×10^6 t/yr from 2004 to 2014, while the SSD percentage at the Three Inlets decreased from 78% to 52%, almost equal to that of the Four Waters (Fig. 10). The significant decline in sediment at the Three Inlets can be directly attributed to the high sediment retention (139×10^6 t/yr) of the TGD after 2003 (Changjiang Sediment Bulletin, 2013). In contrast to the change in SSD at the Three Inlets, the water discharge demonstrated a stable decreasing trend from 2004 to 2014, indicating that the effect of the TGD operation on water discharge was relatively small (Fig. 2C and Fig. 10).

With most sediment being trapped in reservoirs, ‘hungry’ water is prone to erode channel beds and banks to achieve a new equilibrium (Kondolf, 1997). The reach downstream of the TGD, namely, the Yichang-Chenglingji reach, was severely affected, with an average thalweg down-cutting of -2 m and a total channel erosion volume of 841×10^6 m³ from October 2002 to October 2013 (Changjiang Sediment Bulletin, 2007, 2013) (Fig. 11A). Meanwhile, the sites on the mainstream Changjiang River showed a trend of down-cutting to different extents (Fig. 11C). Specifically, the cross-sections of D5, J90 and J186 exhibited serious down-cutting, with an erosion rates of 0.14 m/yr, 0.05 m/yr and 0.4 m/yr, respectively. In contrast, the cross-sections of most sites in the Dongting Lake basin remained unchanged, except for Xinjiangkou, which experienced an erosion rate of 0.1 m/yr (Fig. 11D1). Moreover, the daily mean water level at Shashi and Jianli (in the Jingjiang reach) decreased by 0.56 m and 0.10 m, respectively, between 2002 and 2014. Under the same water discharge conditions, the water level in 2014 was far below that of the pre-TGD period. This phenomenon can be better observed at Shashi (Fig. 11B). Channel degradation with a declining water surface along the Changjiang River further enlarged the topography gradient between the river and the inlets/outlets of Dongting Lake, which played a key role in the reduction of water discharge and facilitated the further reduction of the sediment load entering the Three Inlets from 2004 to 2014.

The enlarged topographic gradient between Dongting Lake and the Changjiang River changed the hydrodynamic conditions within Dongting Lake. The mean and peak flow velocity of the Dongting Lake outlet (Chenglingji station) presented increasing trends from 2007 to 2013 both at high (29.39 m in Jun.) and low water levels (20.84 m in Dec., Jan.) (Fig. 12A). The rising flow velocities indicated that Dongting Lake would provide more water and sediment to the Changjiang River, even during the dry season. Indeed, the SSD of Chenglingji presented a

significant increasing trend after 2007. Furthermore, the sediment budget of Dongting Lake changed from a gain of approximately 120×10^6 t/yr from 1951 to 2003 to a loss of 2×10^6 t/yr from 2004 to 2014, showing that the Changjiang River provided sediment to Dongting Lake before 2003 but extracted sediment from the lake thereafter (Fig. 2B and Fig. 6). Along with the reduction in the sediment source and increase in the outlet flow velocity, Dongting Lake transformed from experiencing deposition to erosion after 2003, which can be confirmed by the shrinking of the Ouchi delta in the western part of the EDL (Fig. 7).

Moreover, the water dispatch modes of the TGD altered the water regime in the Changjiang River downstream from the TGD (Wang et al., 2013). The cross-section at Nanzui, the main entrance of the Three Inlets to the WDL, underwent a slight change from 2007 to 2013, while the flow velocity showed a statistically significant decreasing trend at high water levels (32.26 m in Jun., Jul., Aug.) and an increasing trend at low water levels (28.13 m in Dec., Jan., Feb.) (Fig. 12B). Specifically, during the high water season, the TGD needed to store water for flood control as well as for the water supply in the winter, resulting in a decrease in the water/sediment load and water velocity into Dongting Lake through the Nanzui station (Ou et al., 2012; Wang et al., 2013). In contrast, during the low water season, the TGD released water to satisfy the downstream water demand, causing increases in the water and water velocity at the Nanzui station (Fig. 12B). An increased sediment load at a low water level could partly mitigate the decreased sediment load at a high water level, which made the sediment budget of the WDL change slightly and thus resulted in an insignificant change in the erosion-deposition pattern (Fig. 7A).

However, the water replenishment during winter can hardly reverse the declining trends during the entire dry season at Dongting Lake because less water could flow into Dongting Lake through the Three Inlets due to the serious erosion of the channel of the Changjiang River, and more water was delivered to the Changjiang River. Although the Dongting Lake basin is still likely threatened by flood events in the case of extreme precipitation, the tendency of “less flooding during the flood season and more drying during the dry season” at Dongting Lake is predictable under the impacts of the TGD.

5. Conclusions

The water regime of lakes worldwide has changed drastically under the combined impacts of global climate change and intensive anthropogenic activities. This study focuses on the hydromorphological processes of Dongting Lake and their impact factors. The major findings are as follows:

- 1) The yearly water discharge/SSD of Dongting Lake showed obvious stepwise decreasing trends, except for the water discharge at the Four Waters, even though there were seasonal fluctuations in water discharge and SSD from 1951 to 2014. Meanwhile, the hydrological behavior of Dongting exhibited a tendency towards “less flooding during the flood season and more drying during the dry season”. The rating curves of the Four Waters and Chenglingji remained unchanged from 1951 to 2014, while the rating curve of the Three Inlets shifted from clockwise to counterclockwise from 2004 to 2014.
- 2) The deposition-erosion pattern of Dongting Lake transformed from deposition from 1951 to 2003 to erosion from 2004 to 2014, which was accompanied by a marked drop in the sediment budget of Dongting Lake and the shrinking of the Xiangjiang and Ouchi deltas.
- 3) The hydromorphological processes of Dongting Lake were closely related to climate change and anthropogenic activities. For the Four Waters, basin precipitation dominated the water discharge, while severe soil erosion and reservoir retention induced an increasing SSD during 1967–1980 and a decreasing SSD 1981–2014, respectively. The hydrological variations at the Three Inlets were

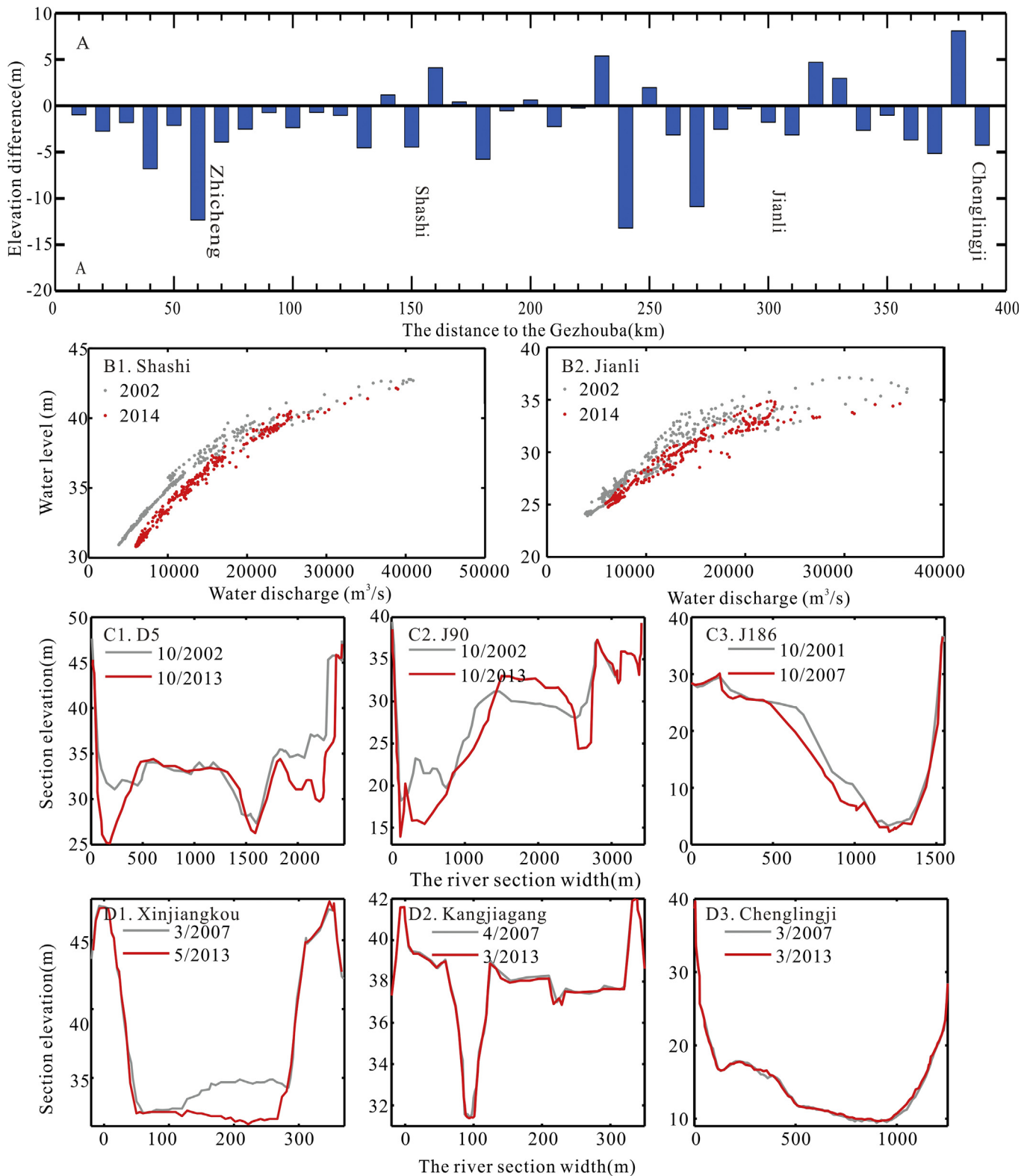


Fig. 11. (A) Thalweg changes along the Changjiang River; (B) Daily water level and water discharge comparison between 2002 and 2014 at Shashi and Jianli; and cross-section variations (C) along the Changjiang River and; (D) Dongting Lake basin.

mainly controlled by intensive anthropogenic activities in the Changjiang River basin, where the Jingjiang Cutoff Project, GD and TGD were the main drivers for the decreases in the water and sediment load from 1967 to 1980, 1981 to 2003, and 2004 to 2014, respectively. The high sediment retention ($139 \times 10^6 \text{ t/yr}$) behind the TGD directly led to drastic reduction in the sediment input from

Changjiang to the Three Inlets. The observable increased SSD output from the lake to Changjiang after 2007 was caused by TGD-induced riverbed incision. Thus, the TGD was responsible for the transformation of the deposition-erosion pattern at Dongting Lake.

Identifying these hydromorphological processes and their associated

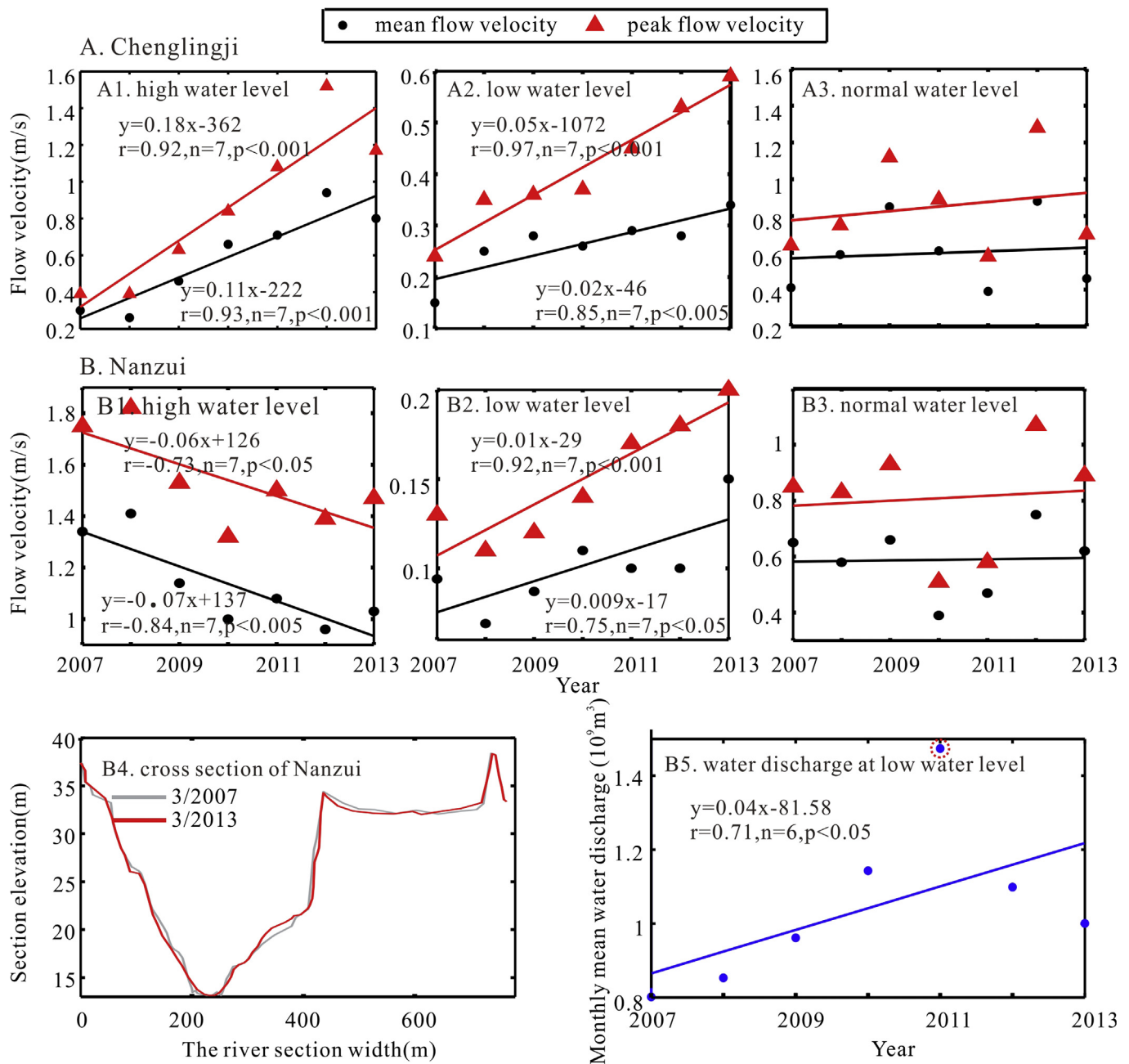


Fig. 12. Flow velocity changes at (A) Chenglingji and (B) Nanzui station at different water levels. For A row: temporal flow velocity variations at A1. high water level (approximately 29.39 m); A2. low water level (approximately 20.84 m); and A3. normal water level (approximately 25.42 m); For B row: temporal flow velocity variations at B1. high water level (approximately 32.26 m); B2. low water level (approximately 28.13 m); B3. normal water level (approximately 30.74 m); cross-section between 2007 and 2013 in B4; and water discharge at low water level in B5.

driving factors is useful for lake management and the regulation of human activity. Our study reveals that anthropogenic activities have gradually become the principle factors of hydromorphological variations at Dongting Lake. Large dams constructed in mainstreams regions have complicated the downstream mechanisms. To maintain the relationship between the lake and rivers and prolong the life of the lake, more systematic research should be conducted.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (NSFC) (41576087, 41571100, 41706093) and the Fundamental Research Funds for the Central Universities. We are very grateful to Professor Marco Borga and the two anonymous reviewers for

their constructive suggestions that helped to improve the previous manuscript.

References

- Alizadeh-Chooabari, O., Ahmadi-Givi, F., Mirzaei, N., Owlad, E., 2016. Climate change and anthropogenic impacts on the rapid shrinkage of Lake Urmia. *Int. J. Climatol.* 36 (13), 4276–4286.
- Bianduo, Bianbaciren, Li, L., Wang, W., Zhaxiyangzong, 2009. The response of lake change to climate fluctuation in north Qinghai-Tibet Plateau in last 30 years. *J. Geogr. Sci.* 19 (2), 131–142.
- Changjiang Sediment Bulletin, 2007. Press of Ministry of Water Resources of the People's Republic of China. < <http://www.cjh.com.cn/> > .
- Changjiang Sediment Bulletin, 2013. Press of Ministry of Water Resources of the People's Republic of China. < <http://www.cjh.com.cn/> > .
- Chen, X.Y., Luo, J., Li, C.Q., 2004. Features and types of soil erosion in granite region of

- Dongting Lake basin. *Bull. Soil Water Conserv.* 24 (1), 60–62 (in Chinese with English abstract).
- Chen, Z.Y., Chen, D.C., Xu, K.Q., Zhao, Y.W., Wei, T.Y., Chen, J., Li, L.Q., Watanabe, W., 2007. Acoustic Doppler current profiler surveys along the Yangtze River. *Geomorphology* 85 (3–4), 155–165.
- China Census for Water in Hunan Province, 2013. Department of Water Resources of Hunan Province. www.hunan.gov.cn.
- Dai, S.B., Yang, S.L., Zhu, J., Gao, A., Li, P., 2005. The role of Lake Dongting in regulating the sediment budget of the Yangtze River. *Hydrol. Earth Syst. Sc.* 6 (9), 692–698.
- Dai, Z.J., Fagherazzi, S., Mei, X.F., Gao, J.J., 2016. Decline in suspended sediment concentration delivered by the Changjiang (Yangtze) River into the East China Sea between 1956 and 2013. *Geomorphology* 268, 123–132.
- Dai, Z.J., Liu, J.T., 2013. Impacts of large dams on downstream fluvial sedimentation: An example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). *J. Hydrol.* 480, 10–18.
- Dai, Z.J., Liu, J.T., Wei, W., Chen, J.Y., 2014. Detection of the Three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta. *Sci. Rep.-UK* 4, 6600. <http://dx.doi.org/10.1038/srep06600>.
- Deng, F., Wang, X.L., Cai, X.B., Li, E.H., Jiang, L.Z., Li, H., Yan, R.R., 2014. Analysis of the relationship between inundation frequency and wetland vegetation in Dongting Lake using remote sensing data. *Ecohydrology* 7 (2), 717–726.
- Deng, M.H., Liu, K.B., Luan, Z.Y., 2012. Study on flow and sediment diversion at Four Inlets of Dongting Lake and tendency and influences of erosion-deposition variation. *Appl. Mech. Mater.* 212–213 (34), 10–19.
- Du, Y., Xue, H.P., Wu, S.J., Ling, F., Xiao, F., Wei, X.H., 2011. Lake area changes in the middle Yangtze region of China over the 20th century. *J. Environ. Manage.* 92, 1248–1255.
- Fan, P., Li, J.C., Liu, Q.Q., Singh, V.P., 2008. Case study: influence of morphological changes on flooding in jingjiang river. *J. Hydraul. Eng.* 134, 1757–1766.
- Gao, J.J., Dai, Z.J., Mei, X.F., Ge, Z.P., Wei, W., Xie, H.L., Li, S.S., 2015. Interference of natural and anthropogenic forcings on variations in continental freshwater discharge from the Red River (Vietnam) to sea. *Quatern. Int.* 380–381, 133–142.
- Greenwood, J.A., Landwehr, J.M., Matalas, N.C., Wallis, J.R., 1979. Probability weighted moments: definition and relation to parameters of several distributions expressible in inverse form. *Water Resour. Res.* 15 (5), 1049–1054.
- Herdendorf, C.E., 1982. Large Lakes of the World. *J. Great Lakes Res.* 3 (8), 379–412.
- Hu, C.H., Fang, C.M., Cao, W.H., 2015. Shrinking of Dongting Lake and its weakening connection with the Yangtze River: analysis of the impact on flooding. *Int. J. Sediment Res.* 30, 256–262.
- Jepsen, S.M., Voss, C.I., Walvoord, M.A., Rose, J.R., Minsley, B.J., Smith, B.D., 2013. Sensitivity analysis of lake mass balance in discontinuous permafrost: the example of disappearing Twelvemile Lake, Yukon Flats, Alaska (USA). *Hydrogeol. J.* 21 (1), 185–200.
- Jiang, W.G., Chen, Z., Lei, X., He, B., Jia, K., Zhang, Y.F., 2016. Simulation of urban agglomeration ecosystem spatial distributions under different scenarios: a case study of the Changsha-Zhuzhou-Xiangtan urban agglomeration. *Ecol. Eng.* 88, 112–121.
- Kendall, M.G., 1970. Rank Correlation Methods. C. Griffin, London.
- Kondolf, G.M., 1997. PROFILE: hungry water: effects of dams and gravel mining on river channels. *Environ. Manage.* 21, 533–551.
- Kummu, M., de Moel, H., Ward, P.J., Varis, O., 2011. How close do we live to water? a global analysis of population distance to freshwater bodies. *Plos One* 6 (6), e205786.
- Lai, X.J., Jiang, J.H., Huang, Q., 2013. Effects of the normal operation of the Three Gorges Reservoir on wetland inundation in Dongting Lake, China: a modelling study. *Hydrolog. Sci. J.* 58 (7), 1467–1477.
- Lai, X.H., Yin, D.W., Finlayson, B.L., Wei, T.Y., Li, M.T., Yuan, W.H., Yang, S.L., Dai, Z.J., Gao, S., Chen, Z.Y., 2017. Will river erosion below the Three Gorges Dam stop in the middle Yangtze? *J. Hydrol.* 554, 24–31.
- Lehner, B., Döll, P., 2004. Development and validation of a global database of lakes, reservoirs and wetlands. *J. Hydrol.* 1 (296), 1–22.
- Lemoalle, J., Bader, J.C., Leblanc, M., Sedick, A., 2012. Recent changes in Lake Chad: Observations, simulations and management options (1973–2011). *Global Planet. Change* 80–81, 247–254.
- Li, N., Wang, L.C., Zeng, C.F., Wang, D., Liu, D.F., Wu, X.T., 2016. Variations of runoff and sediment load in the middle and lower reaches of the Yangtze River, China (1950–2013). *PLoS One* 11 (8), e0160154.
- Mann, H.B., 1945. Nonparametric tests against trend. *Econometrica* 13, 245–259.
- Mcgill, R., Tukey, J.W., Larsen, W.A., 1978. Variations of box plots. *Am. Stat.* 32 (1), 12–16.
- Mei, X.F., Dai, Z.J., Du, J.Z., Chen, J.Y., 2015. Linkage between Three Gorges Dam impacts and the dramatic recessions in China's largest freshwater lake, Poyang Lake. *Sci. Rep.-UK* 5, 18197 1038/srep18197.
- Mei, X.F., Dai, Z.J., Darby, S.E., Gao, S., Wang, J., Jiang, W.G., 2018. Modulation of extreme flood levels by impoundment significantly offset by floodplain loss downstream of the Three Gorges Dam. *Geophys. Res. Lett.* 45, 3147–3155. <http://dx.doi.org/10.1002/2017GL076935>.
- Nakayama, T., Watanabe, M., 2008. Role of flood storage ability of lakes in the Changjiang River catchment. *Global Planet. Change* 63 (1), 9–22.
- Ou, C.M., Li, J.B., Zhang, Z.Q., Li, X.C., Yu, G., Liao, X.H., 2012. Effects of the dispatch modes of the Three Gorges Reservoir on the water regimes in Dongting Lake area in typical years. *J. Geogr. Sci.* 22, 594–608.
- Peng, D.Z., Xiong, L.H., Guo, S.L., Shu, N., 2005. Study of Dongting Lake area variation and its influence on water level using MODIS data. *Hydrolog. Sci. J.* 50, 31–44.
- Sun, L., Fang, J.W., 2002. Investigation on sedimentation in Zhexi reservoir. *J. Sediment Res.* 3, 71–73 (in Chinese with English abstract).
- Sun, Z.D., Lotz, T., Chang, N.B., 2017. Assessing the long-term effects of land use changes on runoff patterns and food production in a large lake watershed with policy implications. *J. Environ. Manage.* 204 (Pt 1), 92–101.
- Tang, R.C., 1999. Impact of river bend cut-off of lower Jingjiang river on the river and Dongting Lake. *Yangtze River* 30 (4), 20–23 (in Chinese with English abstract).
- Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley Pub. Co.
- Wang, J.D., Sheng, Y.W., Gleason, C.J., Wada, Y., 2013. Downstream Yangtze River levels impacted by Three Gorges Dam. *Environ. Res. Lett.* 8 (4), 044012. <http://dx.doi.org/10.1088/1748-9326/8/4/044012>.
- Wang, Y.M., Li, Z.W., Tang, Z.H., Zeng, G.M., 2011. A GIS-Based spatial multi-criteria approach for flood risk assessment in Dongting Lake region, Hunan, Central China. *Water Resour. Manage.* 25, 3465–3484.
- Xia, J.Q., Zhou, M.R., Lin, F.F., Deng, S.S., Lu, J.Y., 2017. Variation in reach-scale bankfull discharge of the Jingjiang Reach undergoing upstream and downstream boundary controls. *J. Hydrol.* 547, 534–543.
- Xiang, L., Lu, X.X., Higgitt, D.L., Wang, S.M., 2003. Recent lake sedimentation in the middle and lower Yangtze basin inferred from ¹³⁷Cs and ²¹⁰Pb measurements. *J. Asian Earth Sci.* 21 (1), 77–86.
- Yang, S.L., Zhang, J., Xu, X.J., 2007. Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implications, Yangtze River. *Geophys. Res. Lett.* 34, 110401. <http://dx.doi.org/10.1029/2007GL029472>.
- Yang, S.L., Zhang, J., Zhu, J., Smith, J.P., Dai, S.B., Gao, A., Li, P., 2005. Impact of dams on Yangtze River sediment supply to the sea and delta intertidal wetland response. *J. Geophys. Res.* Earth. 110, F03006.
- Yin, H.F., Li, C.A., 2001. Human impact on floods and flood disasters on the Yangtze River. *Geomorphology* 41 (2), 105–109.
- Yin, H.F., Liu, G., Pi, J., Chen, G., Li, C., 2007. On the river-lake relationship of the middle Yangtze reaches. *Geomorphology* 85 (3–4), 197–207.
- Yuan, Y.J., Zeng, G.M., Liang, J., Huang, L., Hua, S.S., Li, F., Zhu, Y., Wu, H.P., Liu, J.Y., He, X.X., He, Y., 2015. Variation of water level in Dongting Lake over a 50-year period: implications for the impacts of anthropogenic and climatic factors. *J. Hydrol.* 525, 450–456.
- Zhang, Q., Xu, C.Y., Jiang, T., Wu, Y.J., 2007. Possible influence of ENSO on annual maximum streamflow of the Yangtze River, China. *J. Hydrol.* 333, 265–274.
- Zhang, X., Li, Z.W., Tang, Z.H., Zeng, G.M., Huang, J.Q., Guo, W., Chen, X.L., Hirsh, A., 2013. Effects of water erosion on the redistribution of soil organic carbon in the hilly red soil region of southern China. *Geomorphology* 197, 137–144.
- Zhao, Y.F., Zou, X.Q., Liu, Q., Yao, Y.L., Li, Y.L., Wu, X.W., Wang, C.L., Yu, W.W., Wang, T., 2017. Assessing natural and anthropogenic influences on water discharge and sediment load in the Yangtze River, China. *Sci. Total Environ.* 607–608, 920–932.
- Zhou, Y.Q., Jeppesen, E., Li, J.B., Zhang, Y.L., Zhang, X.P., Li, X.C., 2016. Impacts of Three Gorges Reservoir on the sedimentation regimes in the downstream-linked two largest Chinese freshwater lakes. *Sci. Rep.-UK* 6, 35396. <http://dx.doi.org/10.1038/srep35396>.
- Zhu, L.L., Chen, J.C., Yuan, J., Dong, B.J., 2014. Sediment erosion and deposition in two lakes connected with the middle Yangtze River and the impact of Three Gorges Reservoir. *Adv. Water Sci.* 25 (3), 348–357 (in Chinese with English abstract).
- Zou, W.F., 1992. Soil erosion and sediment deposition in Dongting Lake. *Soil Water Conserv. China* 6, 18–21 (in Chinese with English abstract).